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FACTORS PRODUCING COLUMNAR STRUCTURE IN LAVAS AND ITS OCCURRENCE NEAR MELBOURNE, AUSTRALIA

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The following notes on columnar structure owe their origin to a study of the basalt in the Sydenham area, 15 miles northeast of Melbourne, Australia. There, a young stream, Jackson's Creek, has sunk its bed in the Upper Kainozoic lava flows to a depth of 250′. At some points the Silurian and Upper Ordovician sediments are exposed in its bed but at many other places the stream has not yet reached the level of the old valleys and a great thickness of basalt is exposed to view.

The best columns are found along Jackson's Creek in an area 1¼ miles in length. In it is a low scoria cone of the same age as the lava. Three miles to the north is a line of volcanoes from which the later lava floods came. Of the columns the best perhaps are those known as the Sydenham Organ Pipes. These are 102′ high, are perfectly developed, and give examples of the various structures discussed in this short paper.

1. *Cause of columnar structure.*—The attitude, size, shape, and regularity of the columns depend upon (*a*) the viscosity of the lava; (*b*) the temperature of the lava; (*c*) the rate of cooling; (*d*) the regularity of cooling; (*e*) the homogeneity of the lava. Shallow surface flows are much disturbed by movement and are usually distorted by folded-in masses of scoriaceous material, so that homogeneity is lost. Cooling is irregular and columns do not form. The importance of homogeneity as a factor in columnar formation cannot be emphasized too much. The great controlling factor in the formation of columns is contraction due to cooling. The rock, on cooling, tends to contract but all solids have the power to extend somewhat under tension. When the tension due

to contraction on cooling is able to overcome this power of extension, the rock cracks.

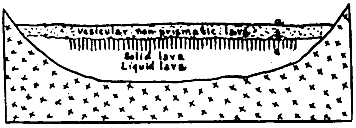

FIG. 1.—Section showing how columns are formed in the brittle solid lava, when tension due to contraction overcomes the expansive power of the lava. Columns are not formed near the surface.

Let us consider in the first place a lava mass cooling from one surface only, the top of the flow (Fig. 1). It is evident that the surface will cool very rapidly owing to the scoriaceous nature of the surface, the convection currents in the air above the heated rock, the volcanic rain (if near a vent), and the collection of water on the warped surface. Thus a solid crust will form over the molten lava and this liquid will cool very slowly because rock is a very poor conductor of heat. While cooling and shrinking in the liquid state, it will adjust itself to the tension by a movement of the liquid, but when the lava solidifies from *b* to *c* (Fig. 1) the rock is subjected to tension in horizontal and vertical directions. The vertical tension is relieved by movement of the liquid beneath *c* and by the shortening of the column *bc*. Vertical tension at this stage does not cause joints in the rock but the horizontal tension can only be relieved by cracking. Mallet[1] puts the temperature of cracking between 315° C. and 500° C., and points out that the temperature is lower when the rate of cooling is very slow. He also shows that if the rock were perfectly homogeneous the surface would be covered with cracks separating the surface into equal areas, i.e., triangles, squares, or hexagons.[2] The smallest amount of work is done by separating the surface into hexagons rather than into squares or triangles. These cracks would extend down into the hot solid rock only a short distance, i.e., to that point where the tension was equal to the extensibility. As the rock cooled, the cracks would extend downward and at the same time the deeper liquid lava would be solidifying and shrinking from two causes: cooling and crystallization. The slower the cooling the more complete the crystallization and therefore the greater the contraction. We thus see that in a homogeneous lava, vertical cracks arranged in hexagons, slowly penetrate the solid lava from above, downward. Solidification of the lava precedes the cracking.

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[1] R. Mallet, *Phil. Mag.*, L (1875), p. 130.

[2] *Op. cit.*, pp. 125–30.

The size of the columns depends chiefly on the temperature and rate of cooling. The more rapidly cooled a flow is the thinner will be the columns.

Owing to the fact that lava masses are seldom homogeneous (on account of included gases, convection currents within, variation in chemical composition, included fragments, etc.) it seldom, if ever, occurs, that only hexagonal prisms are formed. It does not need the fact that olivine crystals have been found divided by vertical joints, nor the preservation of flow structure in glass to show us that the splitting took place in solid lava.[1] It is difficult to imagine liquid or even plastic lava cracking. Tension in that case is relieved by flowage, not by cracking.

For the following reasons the writer believes that columnar structure in basalt is due to slow rather than rapid cooling:

1. Basalt has a very low thermal conductivity and therefore great thicknesses of molten basalt must necessarily cool slowly. The fact that columnar basalt is not well developed where flows are thin appears to be due to two factors: (*a*) heterogeneity of the lava, (*b*) rapid cooling of the thin flow.

2. Cracking takes place in the hot solid rock when the contraction becomes greater than the expansion under tension. The rock is able to resist parting for a longer period when the tension is very slowly increased by slow cooling. If tension is more rapidly increased the flow will break into thin columns or fragments. These statements are based on physical laws. The rate of cooling at the upper surface is much more rapid than at the lower because convection currents in the air above rapidly convey away the heat but the valley floor being a poor heat conductor offers much resistance to the transference of heat. In a thick flow, columns grow from all cooling planes. The upper columns are found to rest on thick basal columns and this fact upholds the statement that the size of columns is determined by rate of cooling.

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[1] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 324; R. B. Sosman, *Jour. Geol.*, XXIV (1916), p. 218.

3. The fact has frequently been recorded[1] that the upper layer of rock is not columnar but fragmental, platy, ropy, or scoriaceo This fact shows that if cooling is rapid, columns are not formed, for the surface layer is cooled with very great rapidity. If cooling is very rapid contraction is likely to cause fragmental partings since the isothermal planes would probably be irregularly spaced through the flow.

4. In the rock sections of columnar basalt examined very little glass was noted, whereas the surface rock contained a considerable amount of glass. The holocrystalline nature of the columnar basalt strongly suggests slow rather than rapid cooling.[2]

2. *Ball-and-socket structure.*—The cross joints are secondary, i.e., they are formed after the columns. This is shown by the fact that they never continue across from one column to another. The vertical columns continue to shrink as they cool. Horizontal contraction simply causes a widening of the vertical joints, but tension in other directions can only be relieved by cracking.

There are necessarily centers of contraction distributed equally along each column (if lava is homogeneous) and the particles will concentrically be drawn toward these points. This causes not only concentric weakenings and cracking but also a well-defined horizontal joint midway between any two centers of contraction (Fig. 2). Mallet[3] says that the concave surfaces face the direction of cooling. This is not true in the areas I have studied, for adjacent columns have the cups facing directions regardless of the cooling surface.

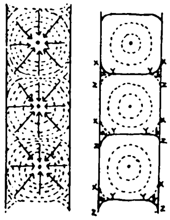

FIG. 2 FIG. 3

FIGS. 2 and 3.—Onion structure and spheroidal weathering. Centers of contraction along the columns cause concentric planes of weakness which, on weathering, develop into the well-known "onion structure." The solid angles *a* and *b*, which tend to break off, are due to these concentric planes of contraction. Ball-and-socket joints are formed between the adjacent spheroids.

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[1] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 325.

[2] *Op. cit.*, p. 331.

[3] R. Mallet, *Phil. Mag.*, L (1875), p. 204; J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 329; R. B. Sosman, *Jour. Geol.*, XXIV (1916), p. 229.

We can say that either the convex or the concave surface faces the direction of cooling. It is also evident that the solid angles, *a* and *b*, are likely to be broken off along *YZ* and *YX* (Fig. 3), since these are planes of contraction and weakness. This seems to explain very simply a well-recognized structure that has given rise to much debate[1] (Fig. 3).

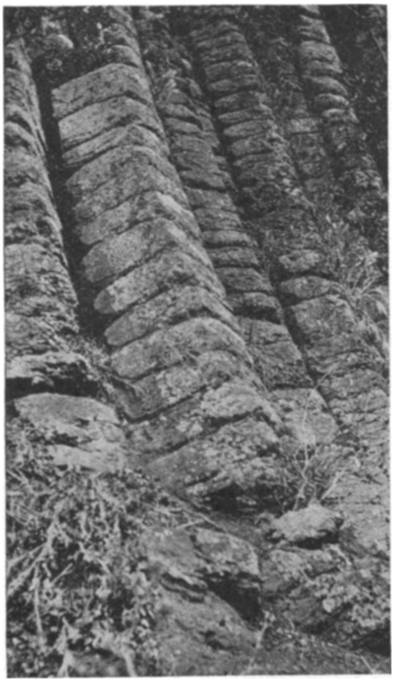

FIG. 4.—"Dutch-cheese" structure. Each spheroid is about eight inches thick. ("Organ Pipes," Sydenham, Australia.)

The above explanation for the ball-and-socket structure also explains the prevalence of spheroids in the columns. I cannot believe that they are due to weathering[2] or segregation, but rather to the concentric spheres of contraction. The spheroids are not found passing from one column to another. In the diagram (Fig. 3) each column is seen to be divided actually or potentially into blocks, each composed of concentric spheres separated by a contraction crack or line of weakness along which weathering will later take place and finally give rise to "onion structure."

3. "*Dutch cheeses.*"—This structure is very common on slightly weathered basalt columns (Fig. 4). The oblate spheroids are seen piled one above the other. They appear to be oblate for this reason: Contraction along *ax* (Fig. 5) is easier than along *ab*,

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[1] T. G. Bonney, *Quart. Jour. Geol. Soc.* (1876), p. 153; R. Mallet, *Phil. Mag.*, L (1875), p. 205; J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886); R. B. Sosman, *Jour. Geol.*, XXIV (1916).

[2] J. Thomson, *British Association Reports* (1863), p. 89; R. Mallet, *Phil. Mag.*, L (1875), p. 220.

because no tearing apart of the crystals is necessary along *ax*. In order that tension in all directions may be approximately equal, *am* must be shorter than *ax*. Therefore, the shape of the spheroids is dependent on the ratio of the tension between *ax* and *am*. The shape of the spheroids is also dependent on the downward pressure of the columns. This pressure tends to resist horizontal cracking and therefore the greater the downward pressure the more prolate the spheroid will be. The actual shape of the spheroid is determined by the downward pressure of the column tending to make it prolate, and the difference in tensions along *am* and *ax* which tends to make the spheroid oblate.

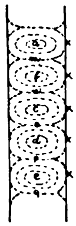

FIG. 5.—Dutch-cheese structure. The shape of the spheroids depends on the balance between the difference in tension between *ak* and *am*, which tends to make the spheroid oblate and the downward pressure of the column tending to make the spheroid prolate.

4. *Chisel structure.*—At the "Sydenham Organ Pipes" horizontal markings $\frac{3}{4}''$ to 2″ apart, are seen circumscribing most of the columns (Figs. 6, 7, and 9). The horizontal lines are found along the whole length of the columns and between them there are peculiar irregularly curved lines similar to those made by roughly chiseling wood (Figs. 7 and 9). The horizontal lines appear to represent successive stages in which the columns were formed, i.e., as cooling proceeded, the vertical plane *abcd* extended to *ef*, then to *gh*, and so on. The "chiselings" curve sometimes to the left, sometimes to the right, and are probably due to the heterogeneity of the rock as it parted.

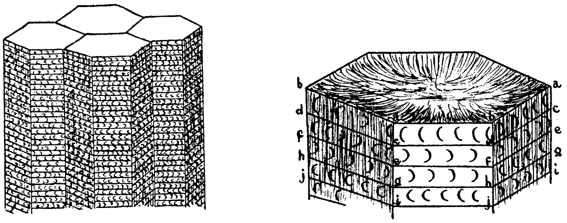

FIG. 6

FIG. 7

FIGS. 6 and 7.—Diagrammatic section showing horizontal bandings *abab*, *cdcd* round the columns. Rough chiselings are shown on each band.

5. *Columns formed by cooling from two opposing surfaces.*—Cooling takes place not only from the upper surface but also from

the floor. The upper surface rapidly parts with its heat by air convection currents and convection along the vertical joints. Heat is only slowly lost from the bottom surface because convection in

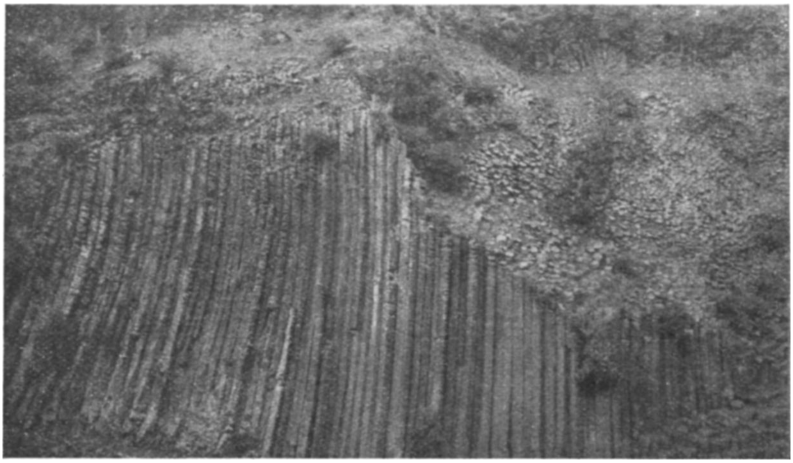

FIG. 8.—"The Organ Pipes." These basaltic columns are 102′ high and are found on Jackson's Creek, Sydenham, Australia.

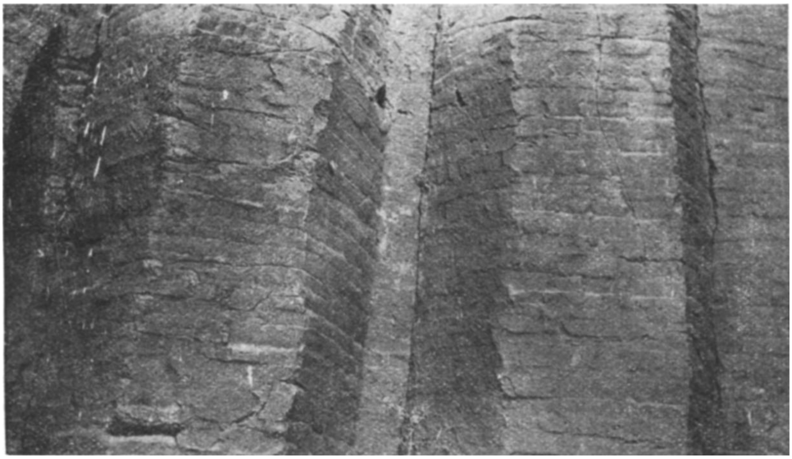

FIG. 9.—Chisel structure. Several basaltic columns are shown with characteristic horizontal banding. In each band the chisel structure can be seen. ("Organ Pipes," Sydenham, Australia.)

the liquid rock seems to be comparatively unimportant, the conductivity of the rock beneath is very low, and the loss of heat by rising gases is unimportant in lowering the temperature of the bottom layers. The isothermal planes will therefore be widely separated in the upper layers and closely packed together in the lower. Two sets of columns will be formed. The upper are long, thin, and often irregular, while the lower set are short, thick, and much more perfect, owing to the homogeneity of the lower lava (Figs. 11 and 12).

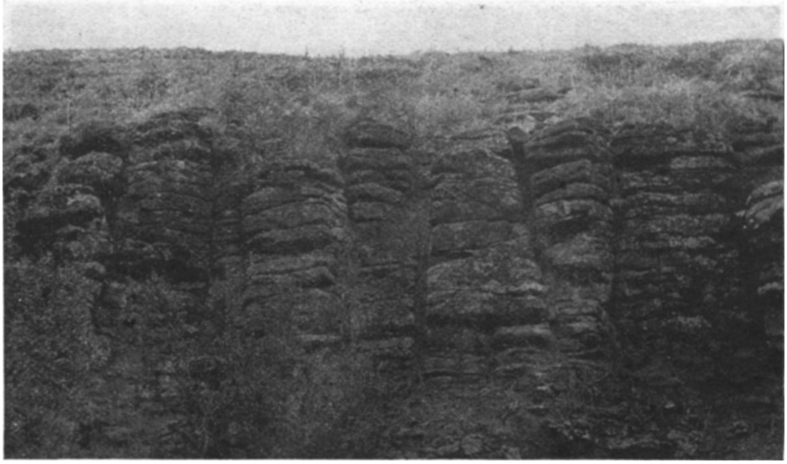

FIG. 10.—Weathered chisel structure. The chisel markings have been weathered off but the horizontal bandings have developed into platy structure. (Jackson's Creek, Digger's Rest, Australia.)

It must be remembered that straight hexagonal columns are produced only in regularly cooling, quiet, homogeneous lavas. The upper part of the flow is more heterogeneous than the lower because (*a*) gases from the lower layers are irregularly distributed near the top; (*b*) the upper surface is churned to some extent by the movement; (*c*) volcanic rain percolates the vesicular lava; (*d*) water may collect on the partially cooled lava. These four factors tend to produce a heterogeneity in the upper part of the flow and therefore only very imperfect columns, if any, are formed.

As the thin upper and the massive lower series of columns approach one another their direction will be influenced by the plane of the isotherms of each series. Both sets are perpendicular to the planes of the isotherms (Fig. 13). Finally the two planes merge into one another and if both sets of columns are vertical, there will be a straight horizontal plane junction which simulates the junction between two lava flow (Figs. 11 and 13), but the absence of vesicles and scoriaceous material, the exact similarity in density and texture of the two series at their junction, and the actual blending of the columns at times show that they belong to the same flow.

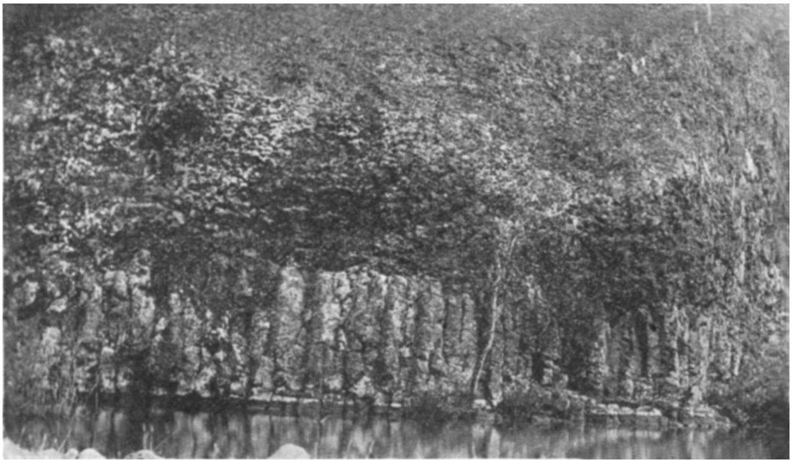

FIG. 11.—Junction of the upper and lower columns of a lava flow. The sharp division suggests the junction of two flows, but only one flow is represented. The lower columns are much more massive than the upper. (Jackson's Creek, Sydenham, Australia.)

The resting of thinner columns on more massive basal ones is very common. They are described by Scrope[1] and Iddings[2] and are well shown at Sydenham. Dykes commonly show the edge of the division plane between two sets of columns.

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[1] G. P. Scrope, *Volcanoes* (1862), p. 94.

[2] J. P. Iddings, *Amer. Jour. Sci.*, XXXI (1886), p. 322.

6. *Columns formed from inclined cooling surfaces.*—The dotted lines on Figure 13 represent the edges of the isothermal surfaces. Columns form at right angles to these surfaces. The isotherms shown in Figures 12 and 13 give data for the rate of formation of the columns, their size, and their direction. The closer the isotherms the larger are the columns because the lava is able to resist a greater tension without cracking when that force is gradually applied. Columns from the two inclined surfaces approach one another and meet along a major joint plane which would be enlarged by drainage. Note that along this major joint the columns curve toward the higher temperatures.

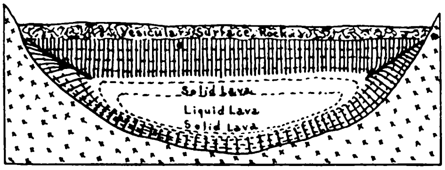

FIG. 12.—Section showing lava cooling from two surfaces, and columns penetrating the solid lava as cooling proceeds. Columns are perpendicular to the isothermal planes and where two cooling surfaces are inclined to one another a major joint plane separates the two sets of columns.

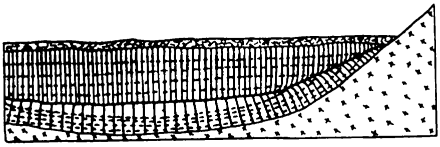

FIG. 13.—Junction of the slender upper columns and the massive basal columns of a lava flow. The junction somewhat resembles the junction between two lava flows.

7. *Bent columns.*—These (Fig. 14) are formed in cases where the isotherms are not parallel to one another. For reasons such as those enumerated below, the cooling in one direction is more rapid than in another. The columns bend in the direction of greatest cooling (Fig. 15). Dotted lines represent edges of isothermal surfaces. The following are suggested causes for change in direction of cooling: (1) presence of scoria, etc., in close proximity to the lava; (2) irregularities in the valley floor; (3) the warping of the lava's upper surface; (4) a scoriaceous and vesicular surface; (5) included gas, water, etc., in the lava; (6) convection currents in the air above the lava; (7) convection currents in the lava; (8) penetration of water into the lava and scoria; (9) rain from the volcano; (10) movement

of the liquid or plastic lava and thereby of the isotherms; (11) rise of steam from an overwhelmed stream; (12) chemical variation in the lava with corresponding change in thermal conductivity.

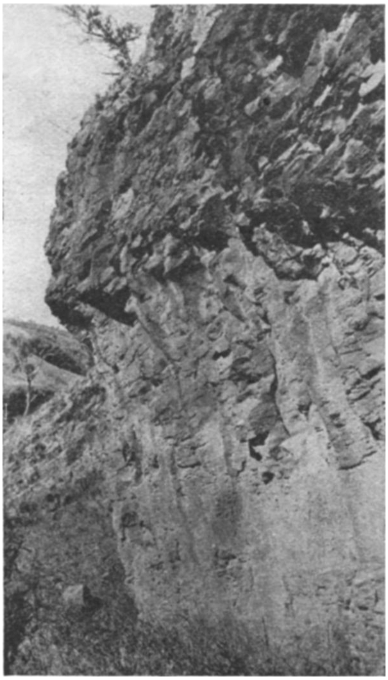

FIG. 14.—Bent columns. (Jackson's Creek, Sydenham, Australia.)

It is not likely that lava columns bend after they are formed, for if lateral pressure were sufficiently strong, it would fracture the brittle columns but not bend them. The plastic state, when the lava would yield to lateral pressure, was lost when the molten mass crystallized.

8. *Convection as a factor on column production.*—R. B. Sosman[1] in 1916, stated that many, if not most, lava columns were due to convection currents in the molten flow. He said convection columns are characterized by the fact that hexagonal columns and angles of 120° predominate, while the majority of contraction columns are pentagonal.[2] After testing some hundreds of columns in the Sydenham area I am unable to agree with him in several respects. The attitude of the columns there stamps them as being definitely due to contraction, not convection, and yet 40 per cent are hexagonal, 22 per cent heptagonal, 22 per cent pentagonal, 13 per cent octagonal and 3 per cent quadrilateral, and the great majority of the angles are

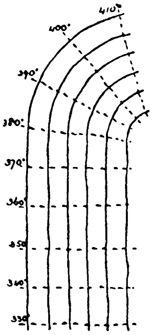

FIG. 15.—Bent columns. Diagram showing the relation of the attitude of the columns to the isothermal planes.

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[1] R. B. Sosman, *Jour. Geol.*, XXIV (1916), pp. 224, 228, 233.

[2] *Ibid.*, pp. 225–26.

between 120° and 130°. From these observations it is clear that it is not safe to classify columns as due to contraction or convection by their shape and angles.

Close to the "Sydenham Organ Pipes" there are a number of huge squat irregular basaltic columns about 10′ in diameter. The flow is thin and the shape of the great blocks seems to be determined by convection which left its record in them by vesicles and when the rock contracted through loss of heat the cracks formed along the lines of vesicles (Fig. 16). The vesicles are pulled round in just the way one would expect if convection currents were the cause. There are centers round which the currents traveled and these tend to be hollowed out leaving holes 3′ to 4′ across. It is possible that the drawn-out vesicles are due to the movement of the lava before it came to rest, but the fact that most of these squat columns seem to have the hollow or nucleus suggests convection. Contraction due to shrinkage subsequently tends to crack the rock along the lines where the currents rose or sank.

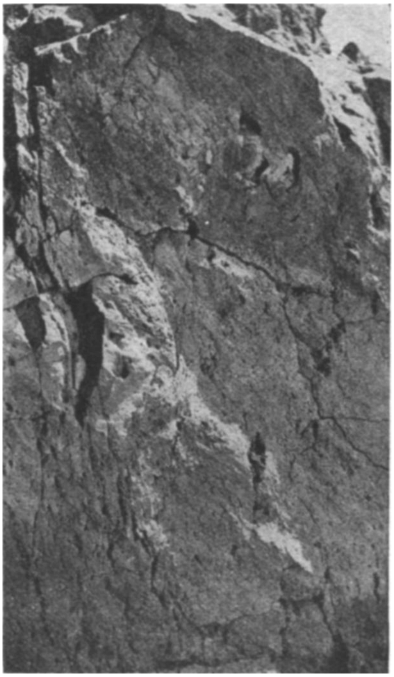

FIG. 16.—Convection currents in basalt. The direction of the vesicles and the occurrence of the nuclei suggest that the molten lava was disturbed by convection currents. The vertical joints occur where the long axes of the vesicles are vertical.

Convection columns in this area are either very unimportant or absent so that the conclusions drawn in R. B. Sosman's paper in the *Journal of Geology*, 1916, do not find confirmation in the area above described.